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Geometry dependence of Auger carrier capture rates into self-assembled quantum dots

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Abstract: We present calculations of Auger carrier capture processes into self-assembled quantum dots. A strong dependence of the Auger capture rate on the size and geometry of the quantum dots is demonstrated.

OCIS codes: (000.6800) Theoretical physics; (320.7130) Ultrafast processes in condensed matter, including semiconductors

In self-assembled quantum-dot (QD) structures, the characteristic timescale of carrier relaxation from wetting-layer (WL) states to discrete QD states is one of the decisive factors for QD device performance. Understanding of the underlying mechanisms, carrier-phonon [1, 2] and carrier-carrier scattering [3, 4] is therefore essential.

Detailed investigations of the QD geometry dependence of processes mediated by carrier-carrier scattering, Auger processes, have not yet been pursued and this is the subject of our paper. We investigate the Auger process where two WL carriers interact leading to the capture of one carrier by the dot and excitation of the other carrier to a higher energy in the WL. The QD is approximated by a cone on a thin WL of thickness d with a nite con nement potential in the e ective-mass approximation. The wavefunctions are determined by a variational approach and are of the same type as in Ref. [1]. States are labeled by an angular momentum quantum number, m, that describes rotation around the z-axis, the ground state by $|S\rangle$ ($m = 0$) and the rst excited state by $|P\rangle$ ($m = \pm 1$). The carrier capture rate is determined by Fermi's golden rule. At low to moderate WL carrier sheet densities, n, the capture rate can be expressed as $R = C_{\mathrm{cs}} n^2$, where C_{cs} is an *Auger coefficient* [4] and c (s) is the type of captured (scattered) carrier ($\{\mathrm{c},\mathrm{s}\} = \{\mathrm{e},\mathrm{h}\}$ for electrons and holes).

We have calculated the Auger coe cients for capture of electrons (left) and holes (right) by varying the dot size. Results are shown in Fig. 1 plotted versus the energy di erence, ΔE, between the WL band edge and the energy level to which the capture takes place, in this case $|S\rangle$ and $|P\rangle$. Scattering by electrons is in general more e cient than scattering by holes, consistent with Ref. [4]. This is because the Coulomb matrix element in C_{cs} decreases with increasing 'momentum transfer' to the scattered carrier. The curvature in the energy dispersion for WL holes is smaller than for electrons, due to the heavier mass. 'Mean momentum transfer' to scattered holes is therefore larger, giving smaller capture rates. The graphs show clearly that for a given process the capture rate depends merely on ΔE, because for a given ΔE the characteristic decay constants of QD wavefunctions are similar. With increasing ΔE the states become more bound to the dot and C_{cs} decreases due to the decreasing overlap of WL and QD wavefunctions.

We show in Fig. 2 the base-angle dependence of C_{cs} for capture into $|P\rangle$ for a truncated cone of constant in-plane radius. Increasing corresponds to approaching a cylinder-shaped dot and increasing the dot volume, which gives decreasing coe cients. For comparison, capture into a non-truncated cone is shown for C_{ee}. The faster decrease with of a non-truncated cone arises due to the localization of the QD wavefunction farther away from the WL. We have also computed phonon-mediated capture by emission of one longitudinal optical (LO) phonon with the same model as in Ref. [1]. Such processes are energetically only allowed for a small range of dot sizes, but are very e cient ($\sim$1 ps at $n = 10^{-15}\mathrm{m}^{-2}$ for one-phonon processes and slightly longer capture times for two-phonon processes [2]). Although Auger carrier capture rates are in general lower than phonon capture rates, the stringent energy conservation in the latter type of process may reduce its e ciency in an inhomogeneously broadened ensemble of dots.

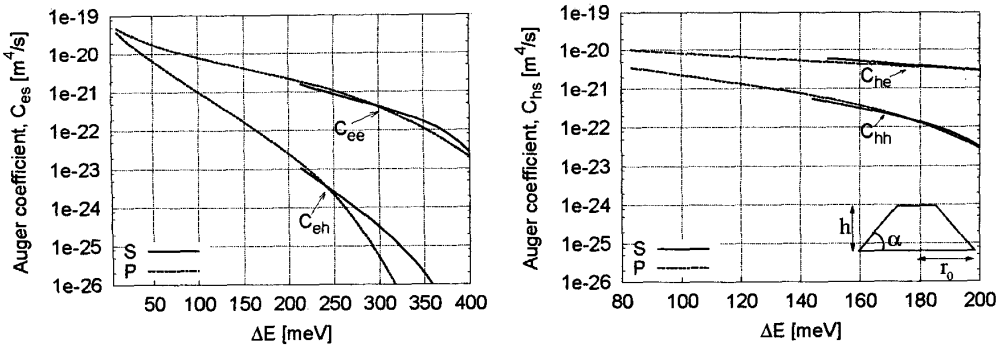

Fig. 1. The Auger capture coefficients C_{es} (left) for electron capture and C_{hs} (right) for hole capture into $|S\rangle$ and $|P\rangle$ plotted versus the energy difference ΔE. The insert of the right graph shows the dot geometry. The minimal ΔE for all curves corresponds to $r_0 = 5.2$ nm, the minimal radius for a truncated cone where we have set $h = 3$ nm. Note the different energy scales of the two graphs that arises from the slower decrease of hole energy levels with dot size. For instance, $\Delta E = 200$ meV for $|P\rangle$ corresponds to $r_0 \approx 7.3$ nm for electrons and $r_0 \approx 13.8$ nm for holes. $V_e = 697$ meV, $V_h = 288$ meV, $m_e = 0.07m_0$, $m_h = 0.34m_0$, $\alpha = 30°$ and $d = 0.33$ nm.

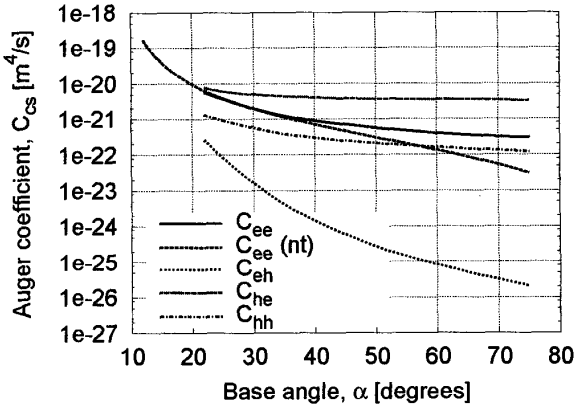

Fig. 2. The Auger capture coefficients as a function of base angle α for capture into $|P\rangle$. For comparison, capture into a non-truncated cone is shown for C_{ee}, labeled "nt". The faster decrease with α of a non-truncated cone arises due to the localization of the QD wavefunction farther away from the WL. We use the same confinement energy, masses, dot height and WL thickness as in Fig. 1 and $r_0 = 7.5$ nm.

References

1. R. Ferreira and G. Bastard, "Phonon-assisted capture and intradot Auger relaxation in quantum dots," *Appl. Phys. Lett.* **74**, 2818–2820 (1999).
2. I. Magnusdottir, A. V. Uskov, S. Bischoff, B. Tromborg, and J. Mørk, "One- and two-phonon capture processes in quantum dots," *J. Appl. Phys.* **92**, 5982–5990 (2002).
3. U. Bockelmann and T. Egeler, "Electron relaxation in quantum dots by means of Auger processes," *Phys. Rev. B* **46**, 15574–15577 (1992).
4. A. V. Uskov, J. McInerney, *et al.*, "Auger carrier capture kinetics in self-assembled quantum dot structures," *Appl. Phys. Lett.* **72**, 58–60 (1998).